LIGO II:
MIT/Caltech Advanced
R&D Program

Gary Sanders

LSC Formation Meeting

Baton Rouge

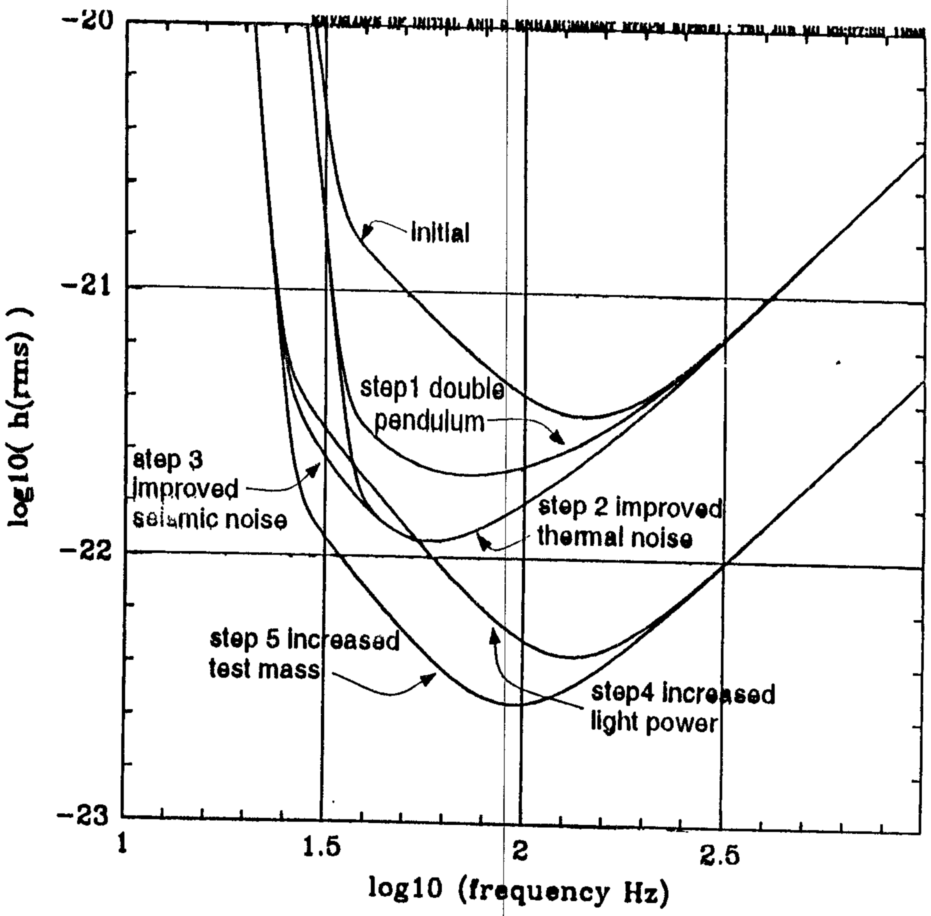
August 14-15, 1997

Evolution

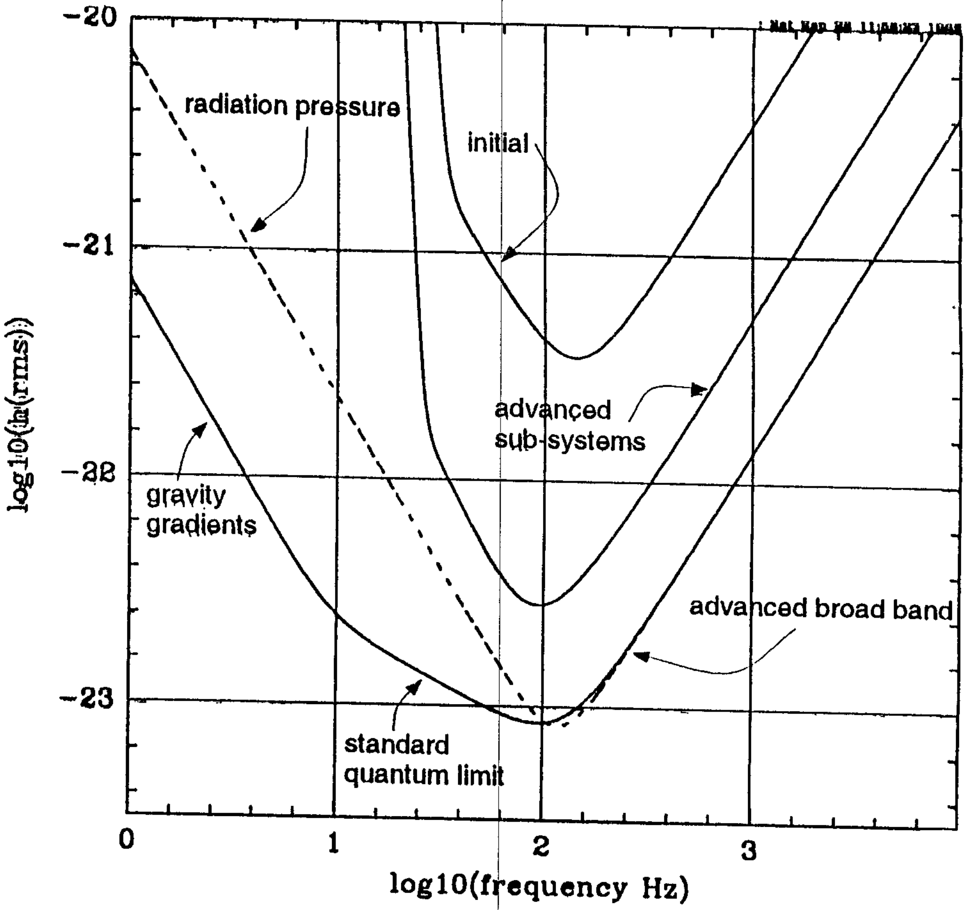
- LIGO Project - 1994
- LIGO Research Community - 1995
- Collaborative Advanced R&D proposals - 1996
- collaboration and Collaboration
- LIGO I and LIGO II - 1997
- LIGO Laboratory - 1997
- LIGO Scientific Collaboration - 1997

- Caltech/MIT LIGO Advanced R&D program will focus on delivering technology basis for LIGO II detector system
  - replacing the "Advanced Subsystems" and "Advanced Detectors" framework of last year

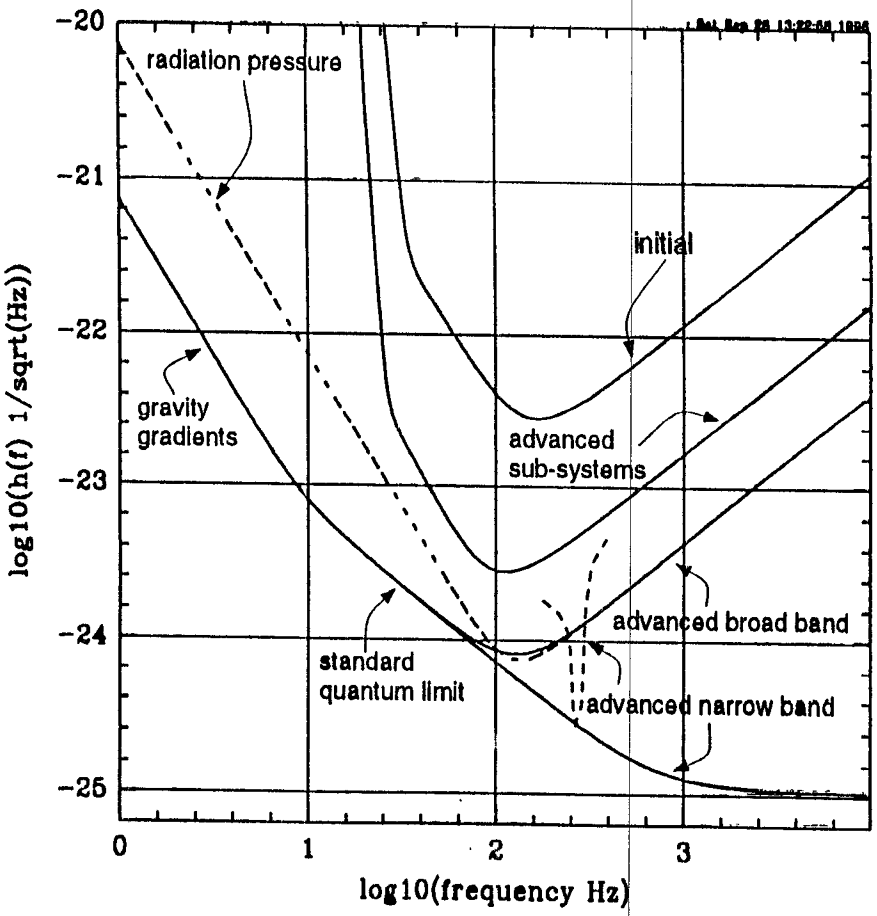
Steps in the Advanced Subsystems Research



h_{rms} Noise Envelopes for Initial LIGO and Advanced Subsystems/Detectors



Amplitude Spectral Strain Noise Expressed as an Equivalent h(f)



Development of Higher Power Lasers

- Motivation and Goal

  ››Higher laser power is an important path toward improved phase sensitivity, leading to better GW sensitivity in shot noise limited regime (above ~150 Hz)

  ››Build one or more 100 W Nd:YAG lasers and test their stability and suitability for LIGO control

  ››Model and understand their characteristics, including frequency noise, intensity noise, pointing stability, and beam quality

- Background and Previous Research

  ››10 W Nd:YAG laser currently under development

  - Collaborative development with Lightwave Electronics
  - MOPA configuration, side-pumped rod geometry
  - Could serve as first stage for 100 W laser

  ›› Superiority of zig-zag slab geometries established for higher powers (greater than 10's of Watts)

  ››Models under development for MOPA and stable-unstable resonator optical configurations

Development of Higher Power Lasers (continued)

- Collaborators and Responsibilities
  - LIGO
    - Interferometer modelling to develop requirements
    - Participate in testing with Galileo and ACIGA
    - Possible work with Lightwave
  - Galileo (Stanford)
    - Fabricate and test high power MOPA
  - ACIGA (Adelaide)
    - Continued development of stable-unstable resonator design
  - GEO
    - ?

Development of Higher Power Lasers (continued)

- Work Plan and Schedule
  - Evaluate performance of 10 W LIGO laser -- 3/98 (LIGO, Galileo)
  - Develop laser requirements for LIGO-II interferometer -- 7/98 (all)
  - Build 40 W stable-unstable resonator laser -- 12/98 (ACIGA)
  - Characterize 40 W stable-unstable resonator laser -- 5/99 (ACIGA, LIGO)
  - Upgrade to 100 W stable-unstable resonator laser -- 12/00 (ACIGA)
  - Characterize 100 W stable-unstable resonator laser -- 5/01 (ACIGA, LIGO)
  - Build 40 W MOPA laser -- 12/98 (GALILEO)
  - Characterize 40 W MOPA laser -- 5/99 (GALILEO, LIGO)
  - Build 100 W MOPA laser -- 6/00 (GALILEO)
  - Characterize 100 W MOPA laser -- 12/00 (GALILEO, LIGO)
  - Decision on LIGO-II high power laser configuration -- 9/01 (all)

Optics For Higher Power

- MOTIVATION

  ››Reduce Shot noise by decreasing cavity loss due to surface structure, surface and bulk absorption, and degradation.

- BACKGROUND AND PREVIOUS RESEARCH

  ››LIGO Pathfinder has generated momentum in industry for production of high quality optics. This momentum can be maintained with the following development programs while valuable resources are still available.

- WORK PLAN

  ››Surface Loss

  —Coating Uniformity development. Investigation of alternate Coating Materials.

  —Polishing development. Improvement in Figure as well as supersmoothing.

  —Metrology development to support Coating and Polishing improvements.

Optics For Higher Power

Work Plan, continued

- ››Bulk Absorption
  - —Material Development. Industry is considering production of Low absorption glass
  - —Investigate active compensation for thermal lensing
- ››Degradation Loss
  - —Investigate Surface and Bulk damage mechanisms in high CW fields
  - —Investigate contamination processes, prevention and cleaning

- COLLABORATORS, RESPONSIBILITIES AND SCHEDULE
  - ››LIGO/Industry: Coating, Polishing, Metrology
    - —Small scale development in parallel with LIGO Fabrication, Large Scale applications beginning early in 1999.
  - ››LIGO/Eastern Michigan/Industry: Low loss material
    - —Test and development 1998, 1999. Full scale test 2000

Optics For Higher Power

Collaborators, Responsibilities... continued

- LIGO: Investigate active compensation, damage mechanisms and contamination processes.
  - 3 year program beginning in 2000

Adaptive Core Optics

- Problem: LIGO I sees thermal effects at 10 W laser power.[1] > 100 W required for "Advanced" shot noise sensitivity.
- Several thermal effects foreseen:
  - cavity mode distortion --> poor coupling
  - differential cavity mode mismatch --> contrast defect
  - recycling cavity sideband loss for power-recycled Schnupp scheme
- Several strategies proposed:
  - Insensitive configuration (RSE), readout (all-resonant SB, no resonant SB)
  - lower bulk- and surface-loss, CTE, dN/dT and higher κ_{th} optics
  - Adaptive Core Optics

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[1] Recycling mirror curvature specifications must counteract calculated ITM thermal lens to avoid significant performance penalty.

Research Program Components

- Modeling
  - Couple quasi-static thermal FEA with FFT-based and/or modal expansion-based optical mode propagation (a portion of Adv. Configs. research topic)
- Sensing research
  - Modified Schack-Hartmann sensors
  - "Super Wavefront Sensor" (SWFS)
    - > "bull's eye" RF detectors and rectilinear PD arrays
    - > strobed video detect/demod methods
  - Dithering & synchronous image processing
- Actuation research
  - scanned auxiliary ('heater') laser (e.g., CO_2; highly general, "brute force")
  - radiative coupling control (e.g., filaments & low-ε shields; "finesse")

Sapphire for Advanced LIGO

- Motivation: Superior bulk material properties.
  - ››Thermal noise: $dz_{\text{rms,thermal}} \sim (\rho\, v_{\text{sound}}\, Q)^{-1/2} \sim .06$x Silica

    ρ= density ~ 1.9 x fused silica

    v_{sound} ~ 1.8 x fused silica

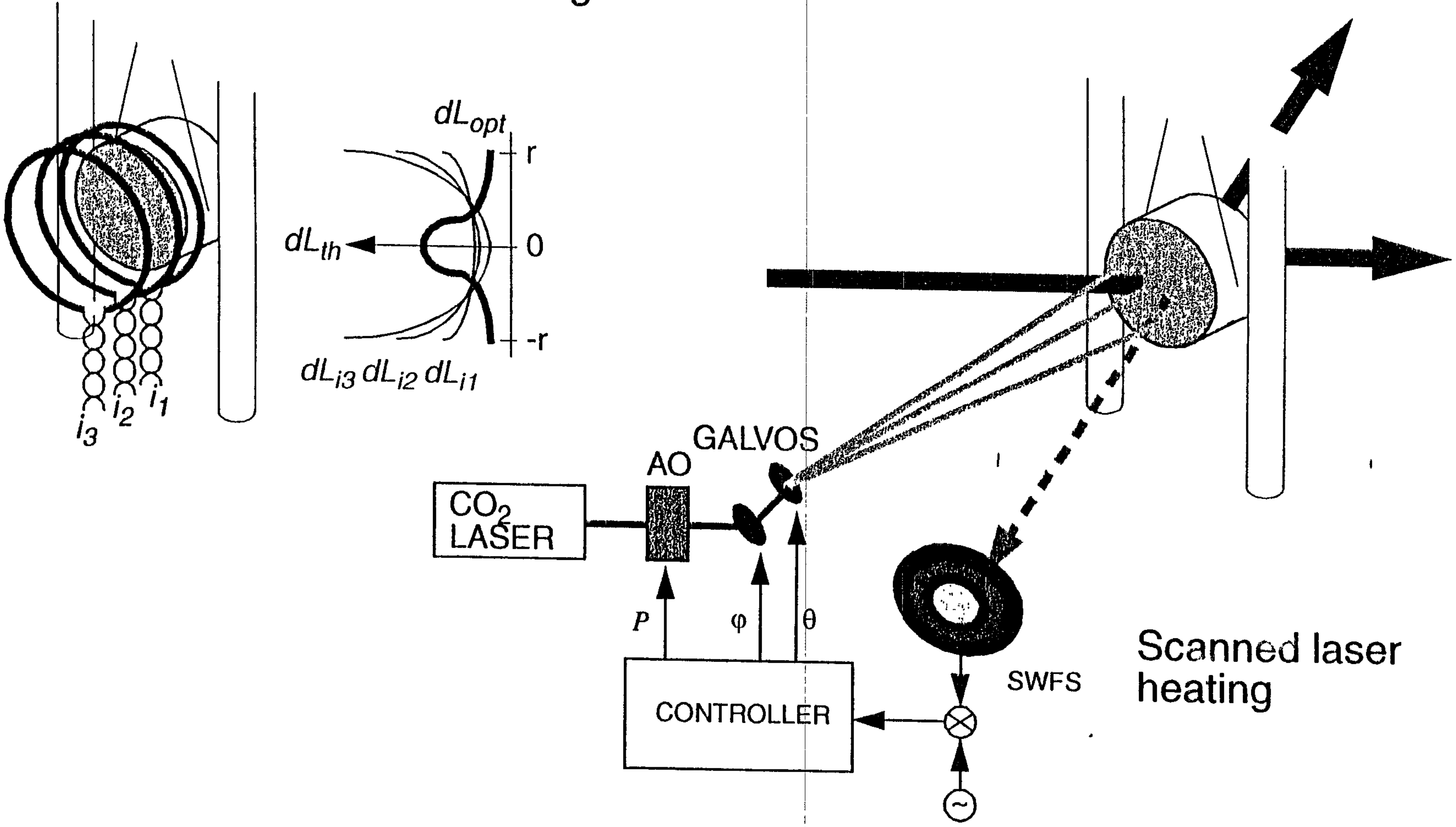
    $Q_{\text{mechanical}}$ demonstrated > 50 x typical fused silica
  - ››Thermal lens: dominant (trans.) distortion $\propto \beta/\kappa \sim .05$x Silica

    β = d(refractive index)/dT ~ 2 x fused silica

    κ = thermal conductivity ~ 45 x fused silica
  - ››TM mass: quantum limit ~ $\text{Mass}_{\text{TM}}^{-1/2}$
  - ››Mechanical design flexibility potential: $\text{modulus}_Y \sim 5$x Silica
    - —Monolithic suspensions, attaching directly to TM
    - —Reduced suspension induced optical distortion.
- Goal: LIGO I sized sapphire without retreat from Silica features:
  - ››Large area precision superpolish.
  - ››High, large volume, optical uniformity ($\Delta n_{\text{effective}} < 5\times10^{-7}$)
  - ››Low volume absorptivity @1.06µm (< 5ppm/cm)

Actuation concepts (prelim.)

Radiative load tailoring



Scanned laser heating

Sapphire for Advanced LIGO

- Prospect: individual samples (<ϕ 8cm) have already demonstrated these goals.
- Present status: contract (Crystal Systems) and MOU (SIOM, Shanghai) to produce ~half size blanks (along azimuthally uniform “c” axis)

››Use Pathfinder related metrology to evaluate vs fused silica

››reproducible high bulk uniformity (difficult for “c” axis growth) and low absorption of particular concern.

- Further necessary R&D

››Pathfinder like program to identify polish process (comparable to LIGO I, fused silica).

››Similar coating development program (coef. thermal expansion >10x silica presents new challenge for large area multi-layer coatings).

››Problem of TM attachments: engineer new approach.

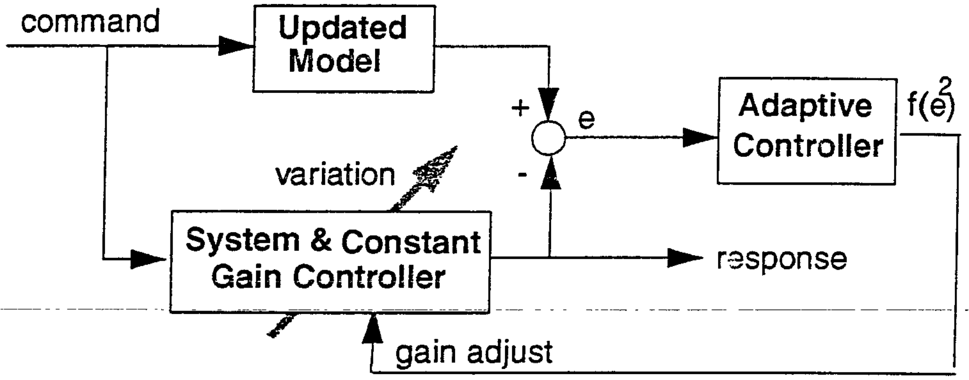
—“Dressed” Q test bed

Advanced Control Techniques (Adv. R&D Proposal)

- Motivation
  - Detection Mode Control System design for LIGO assumes that optical parameters don't drift---but they do (changes due to misalignment, mirror degradation, etc.)
  - Resulting performance and robustness of interferometer is sub-optimal
- Proposal
  - Use Adaptive Control and System Identification to keep interferometer locked indefinitely with optimal performance
    - Adapt Parameters in Detection Mode Length Control System to improve performance and robustness
    - Identify physics of why interferometers unlock (little fundamental understanding of unlocking mechanisms)
    - Design adaptive controller to desensitize interferometer to unlocking mechanisms

Advanced Control Techniques (contd. 2)

- Background and Previous Research
  - ›› Large body of literature on Adaptive Control and System ID (Astrom and Whittenmark, Widrow and Stearns, etc.)



Block Diagram of Model Reference Adaptive Control System

- Research Plan
  - ›› Caltech 40 m prototype as testbed
    - — System ID studies to identify drifting optical plant matrix
    - — Adaptive control design testbed for Detection Mode controller
    - — Study mechanisms that throw interferometer out of lock and propose ways to eliminate problem

LIGO Lab ‘Stochastic Forces’ Research

David Shoemaker

Research that targets physical motions of the test masses

- thermal noise
- seismic noise
- ‘excess’ noise - e.g., stress release
- control forces and hierarchies to allow interferometer ‘locking’ and operation

Principal focus: LIGO II, ~2003

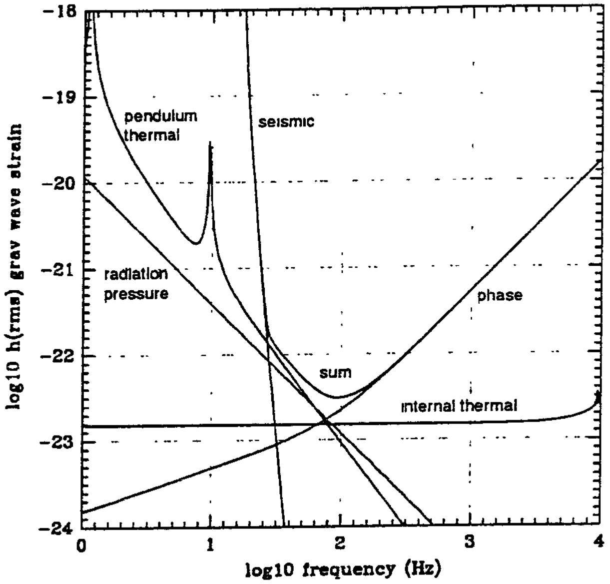
- double pendulum suspension for test mass
  - possible changes in test mass material (sapphire??)
  - certainly changes in fibers (probably fused quartz)
- associated changes in rest of system
  - ~~some damping/taming of LIGO I passive isolation~~
  - active isolation, probably external to vacuum
  - control hierarchy to get signals away from test masses

Collaboration an important aspect of this work

- GEO, Stanford, JILA, Syracuse, PSU, LSU, Moscow
- our plan designed to be complementary
- capitalize on LIGO experience and infrastructure

Structure of LIGO Lab effort

1) Approach problem from a 'systems' view



- establish the performance requirements (baseline: 'Advanced Subsystems')
- determine the site environment, constraints from existing systems
- learn what is good in present LIGO suspension designs
- learn from collaborators what conceptual designs work

2) Modeling

- combine environmental info, LIGO I suspension characterization, concepts
- refine concepts; special effort to reduce/eliminate test mass actuation
- generate design questions to be answered by experiments

3) Control and configuration prototyping:

- build up low-performance partial suspension prototypes, in-air or bell jars
- tests for actuation, dynamics, practical questions (alignment)

Prototype studies of thermal/excess noise

Trial designs need noise testing at design sensitivity

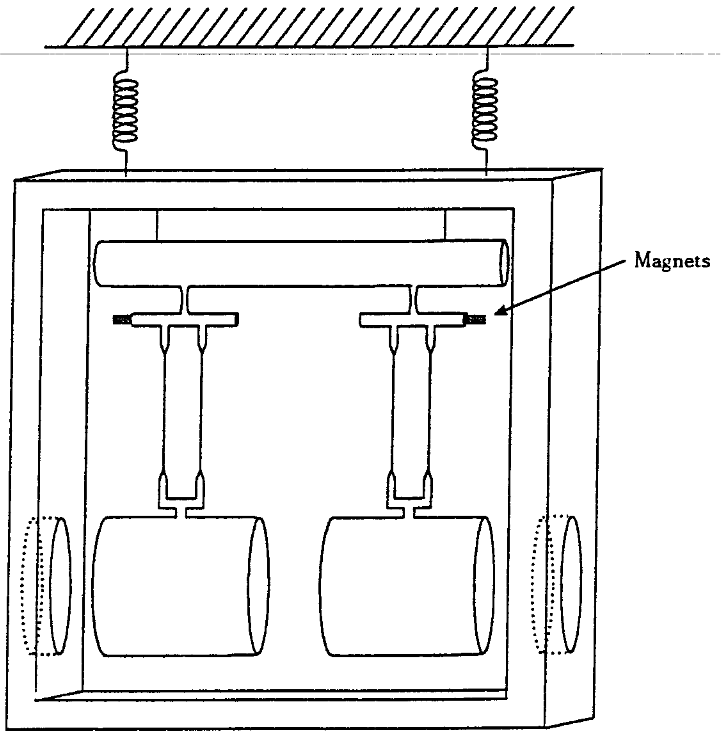
- creaking, actuator noise/coupling, and thermal noise

Special purpose interferometer

- targets displacement noises
- designed to suppress sensitivity to environment
- no attempt to reach phase or strain sensitivities; not a michelson

onfiguration

- short (mm) test cavity, longer referece cavity to hold down frequency noise
- built inside single vacuum chamber, on common seismic isolation 'stack'
- will test partial suspension systems in iterative development phase



Testing of Suspension Systems

Systems are a key issue in suspension design

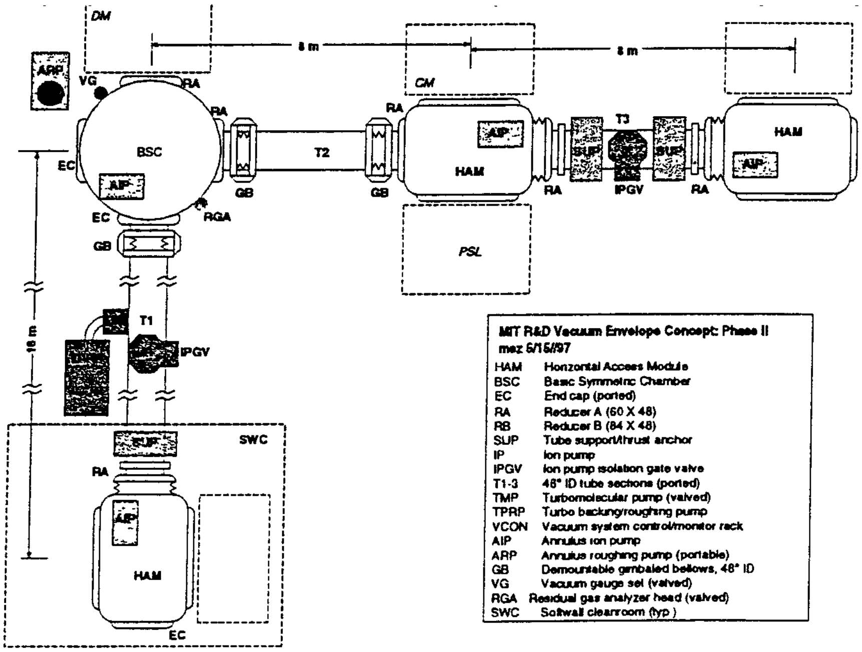
- some tests must include the dynamics of the entire isolation system
- scaling laws helpful, but actual placement of resonances, coupling critical
- need a test facility which includes all LIGO components from ground up

Full-scale tests of prototypes

- single suspensions for actuator, control tests
- pairs of suspensions for transfer functions, pointing
- complete interferometers for end-to-end tests, including noise performance

Pre-installation testing

- as a 'last stop' before LIGO
- minimize down time at the sites; practice installation and debugging



MIT R&D Vacuum Envelope Concept: Phase II
mez 5/15/97

HAM	Horizontal Access Module
BSC	Basic Symmetric Chamber
EC	End cap (ported)
RA	Reducer A (60 X 48)
RB	Reducer B (84 X 48)
SUP	Tube support/thrust anchor
IP	Ion pump
IPGV	Ion pump isolation gate valve
T1-3	48" ID tube sections (ported)
TMP	Turbomolecular pump (valved)
TPRP	Turbo backing/roughing pump
VCON	Vacuum system control/monitor rack
AIP	Annulus ion pump
ARP	Annulus roughing pump (portable)
GB	Demountable gimbaled bellows, 48" ID
VG	Vacuum gauge set (valved)
RGA	Residual gas analyzer head (valved)
SWC	Softwall clearroom (typ)

Milestones

Significant milestones in design process

- establishing requirements, interfaces, design constraints (~now)
- determining the state of the art, lessons from initial LIGO
- conceptual design (1998)
- construction and test of lab prototypes of aspects of design (1999)
- initial complete prototype testing (2000)
- test of final design (2001)
- qualification of suspensions to be installed (2002)

The Thermal Noise Interferometer

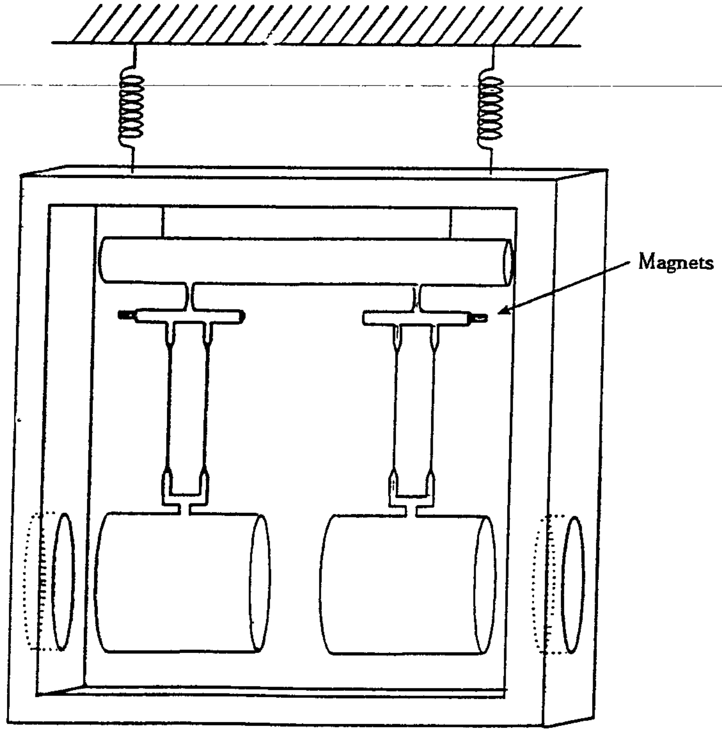
- Caltech - Ken Libbrecht, Eric Black
- The TNI Concept:

  ››A Suspended Interferometer for Direct Measurement of Displacement Noise

  - instrument optimized for displacement noise measurements
  - direct determination of overall displacement noise performance
- The Need for Direct Displacement Noise Measurements:
  - Far-Off-Resonance Thermal Noise Hasn't Been Adequately Measured
  - The Possibility of a Non-Uniform Material Loss Function (e.g. from coatings) adds Uncertainty to Thermal Noise Calculations. Measuring Q is not sufficient for calculation of thermal noise.
  - Can Directly Measure Excess Noise (e.g. from material creep)
  - Examination of Potential Technical Noise Sources: actuator noise, mass charging, etc.
  - Test and Characterize Advanced LIGO Masses before Installation

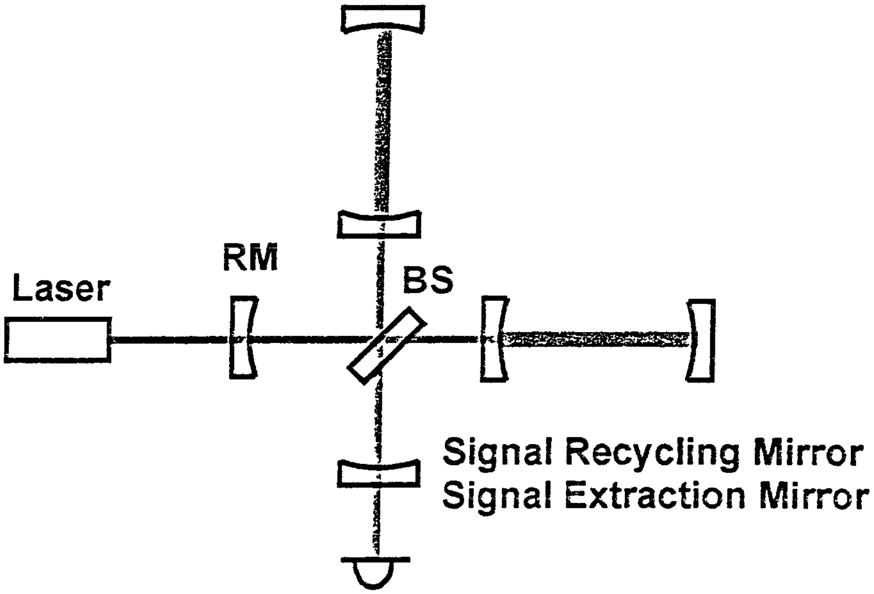
TNI Test Masses -- Mark I

- short cavity lengths --> reduced laser stability requirements
- high finesse --> low shot noise (along with small cavity storage time)
- convex/concave cavity geometry --> large beam spot size
- welded silica double suspension --> low thermal noise
- single bar suspension --> common-mode rejection of seismic noise



Signal Recycling and Resonant Sideband Extraction I

- Motivation
  - ››Narrow band operation - better sensitivity with reduced bandwidth
- Background
  - ››**Signal Recycling** (Invented by B. Meers)
    - —Signal recycled by signal recycling mirror
  - ››**Resonant Sideband Extraction** (Invented by J. Mizuno)
    - —Signal extracted by signal extraction mirror



Signal Recycling and Resonant Sideband Extraction II

- Previous Research
  - ››Experiment done by non-ideal configuration for LIGO
    - —No arm cavities for SR, No recycling mirror for RSE
    - —External modulation
- Work Plan